US009437238B2

(12) **United States Patent**
Pell et al.

(10) **Patent No.: US 9,437,238 B2**
(45) **Date of Patent: *Sep. 6, 2016**

(54) **SYSTEM AND METHOD OF PROCESSING SEISMIC DATA ON A CO-PROCESSOR DEVICE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 9 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/138,457**

(22) Filed: **Dec. 23, 2013**

(65) **Prior Publication Data**

US 2014/0115203 A1 Apr. 24, 2014

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/597,466, filed on Aug. 29, 2012, now Pat. No. 8,825,929, which is a continuation-in-part of application No. 12/184,144, filed on Jul. 31, 2008, now Pat. No. 8,281,056.

(51) **Int. Cl.**

G06F 13/12	(2006.01)
G11B 20/00	(2006.01)
G01V 1/22	(2006.01)
G06F 13/38	(2006.01)
H03M 7/30	(2006.01)
G06F 3/06	(2006.01)

(52) **U.S. Cl.**

CPC ***G11B 20/00007*** (2013.01); ***G01V 1/22*** (2013.01); ***G06F 13/385*** (2013.01); *G06F 3/0613* (2013.01); *G06F 3/0641* (2013.01); *G06F 3/0674* (2013.01); *G06F 2212/401* (2013.01); *H03M 7/30* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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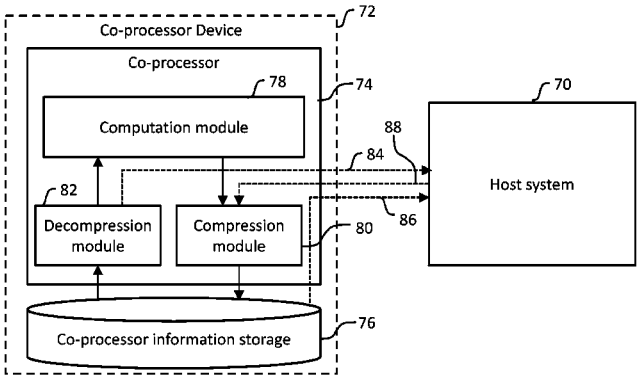
(57) **ABSTRACT**

A system and method for processing seismic data on one or more co-processor devices that are operatively coupled to a host computing system via a communications channel. The compression of input data transmitted to the co-processor device and/or the size of the storage provided on the co-processor device may enhance the efficiency of the processing of the data on the peripheral device by obviating a bottleneck caused by the relatively slow transfer of data between the host computing system and the co-processor device or by the relatively slow transfer of data within the co-processor device between the co-processor information storage and the co-processor.

3 Claims, 6 Drawing Sheets



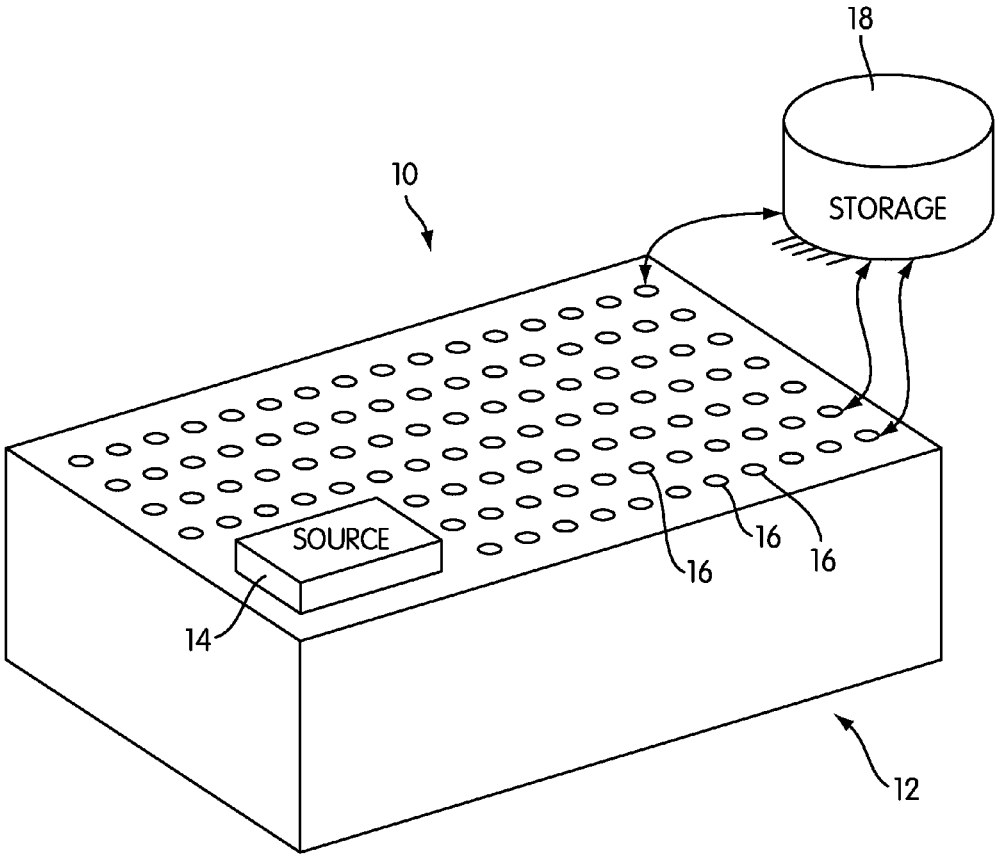


FIG. 1

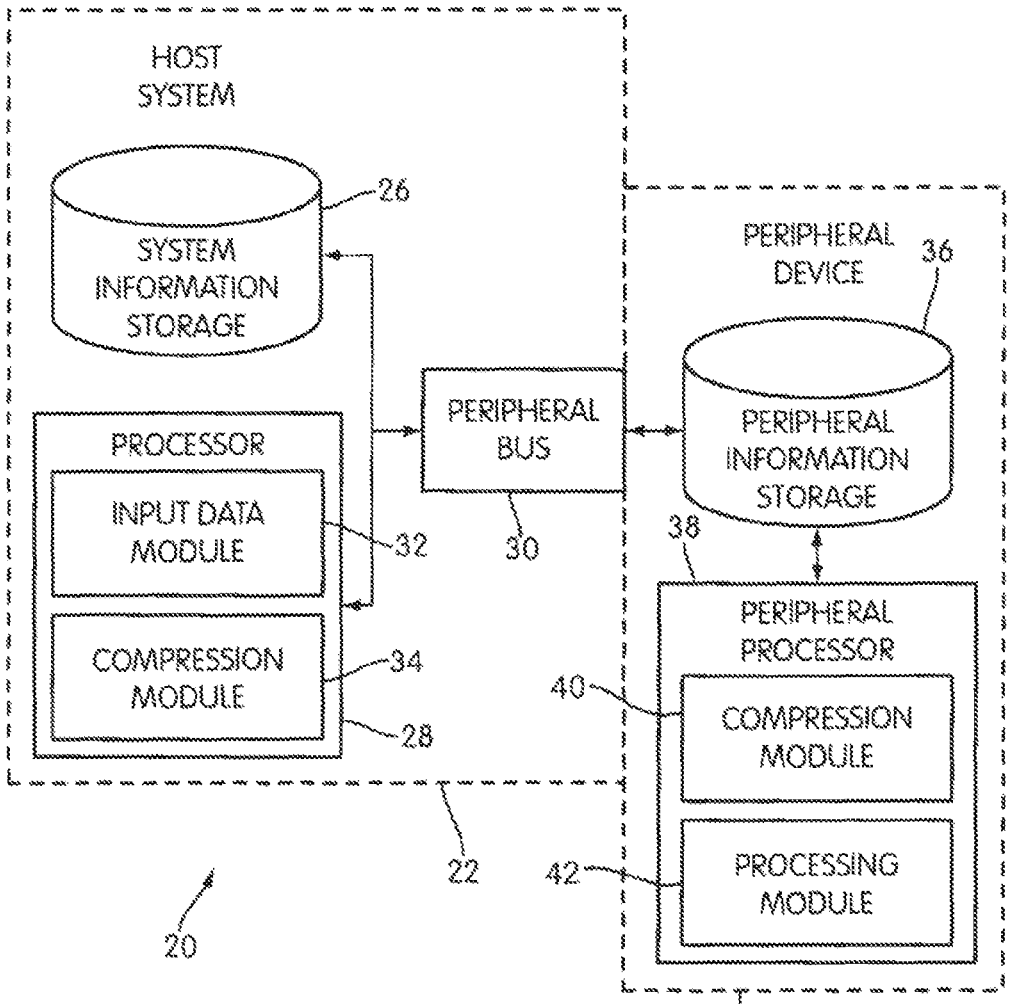

HOST SYSTEM
26
SYSTEM INFORMATION STORAGE
PROCESSOR
INPUT DATA MODULE
32
COMPRESSION MODULE
34
28
PERIPHERAL BUS
30
PERIPHERAL DEVICE
36
PERIPHERAL INFORMATION STORAGE
38
PERIPHERAL PROCESSOR
40
COMPRESSION MODULE
42
PROCESSING MODULE
22
20
24

FIG. 2

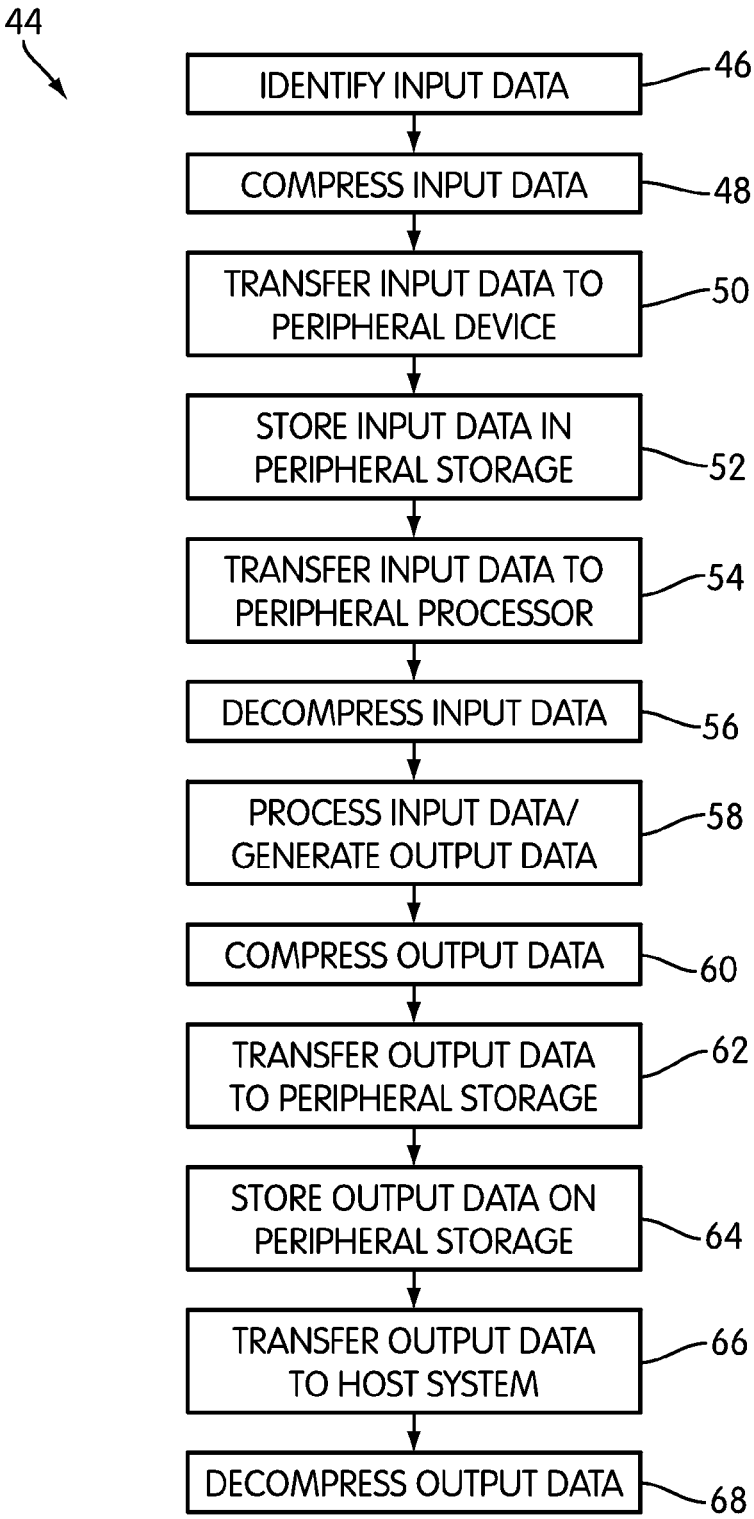

44
IDENTIFY INPUT DATA
46
COMPRESS INPUT DATA
48
TRANSFER INPUT DATA TO PERIPHERAL DEVICE
50
STORE INPUT DATA IN PERIPHERAL STORAGE
52
TRANSFER INPUT DATA TO PERIPHERAL PROCESSOR
54
DECOMPRESS INPUT DATA
56
PROCESS INPUT DATA/ GENERATE OUTPUT DATA
58
COMPRESS OUTPUT DATA
60
TRANSFER OUTPUT DATA TO PERIPHERAL STORAGE
62
STORE OUTPUT DATA ON PERIPHERAL STORAGE
64
TRANSFER OUTPUT DATA TO HOST SYSTEM
66
DECOMPRESS OUTPUT DATA
68

FIG. 3

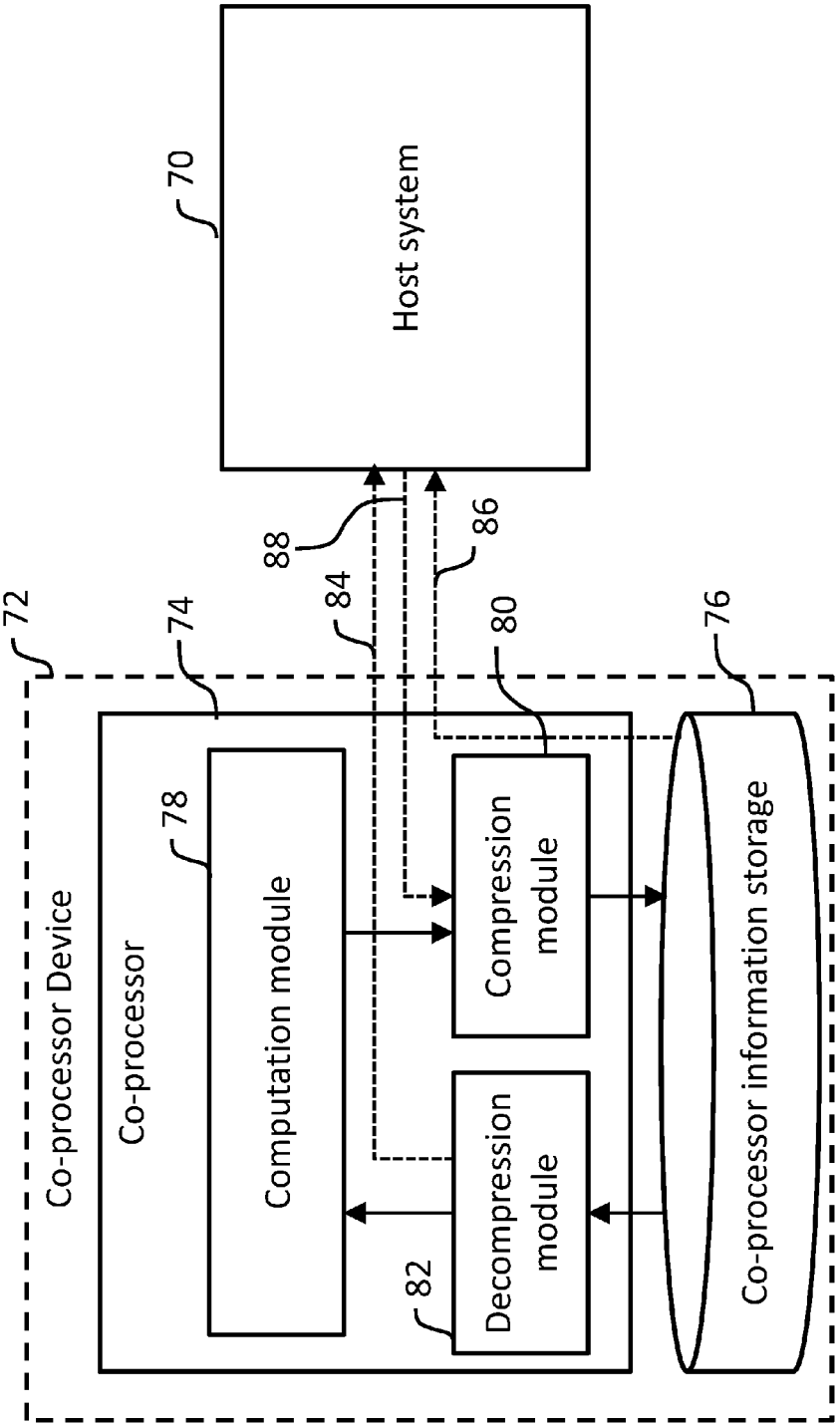

70
Host system
88
86
84
72
74
80
76
78
Co-processor Device
Co-processor
Computation module
Compression module
Co-processor information storage
82
Decompression module

FIG. 4

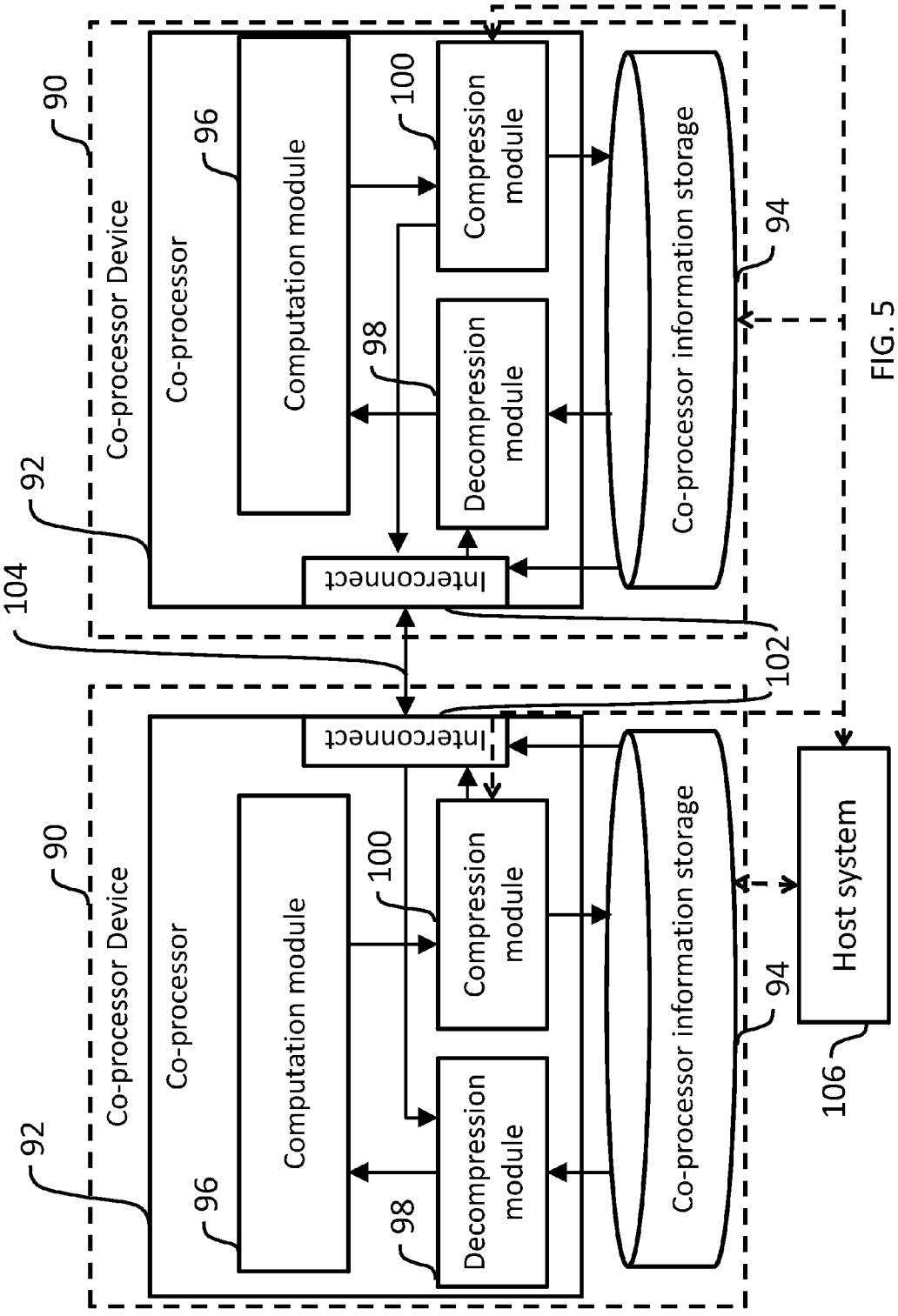

90
Co-processor Device
92
Co-processor
96
Computation module
100
Compression module
98
Decompression module
Interconnect
Co-processor information storage
94
104
102
Host system
106

FIG. 5

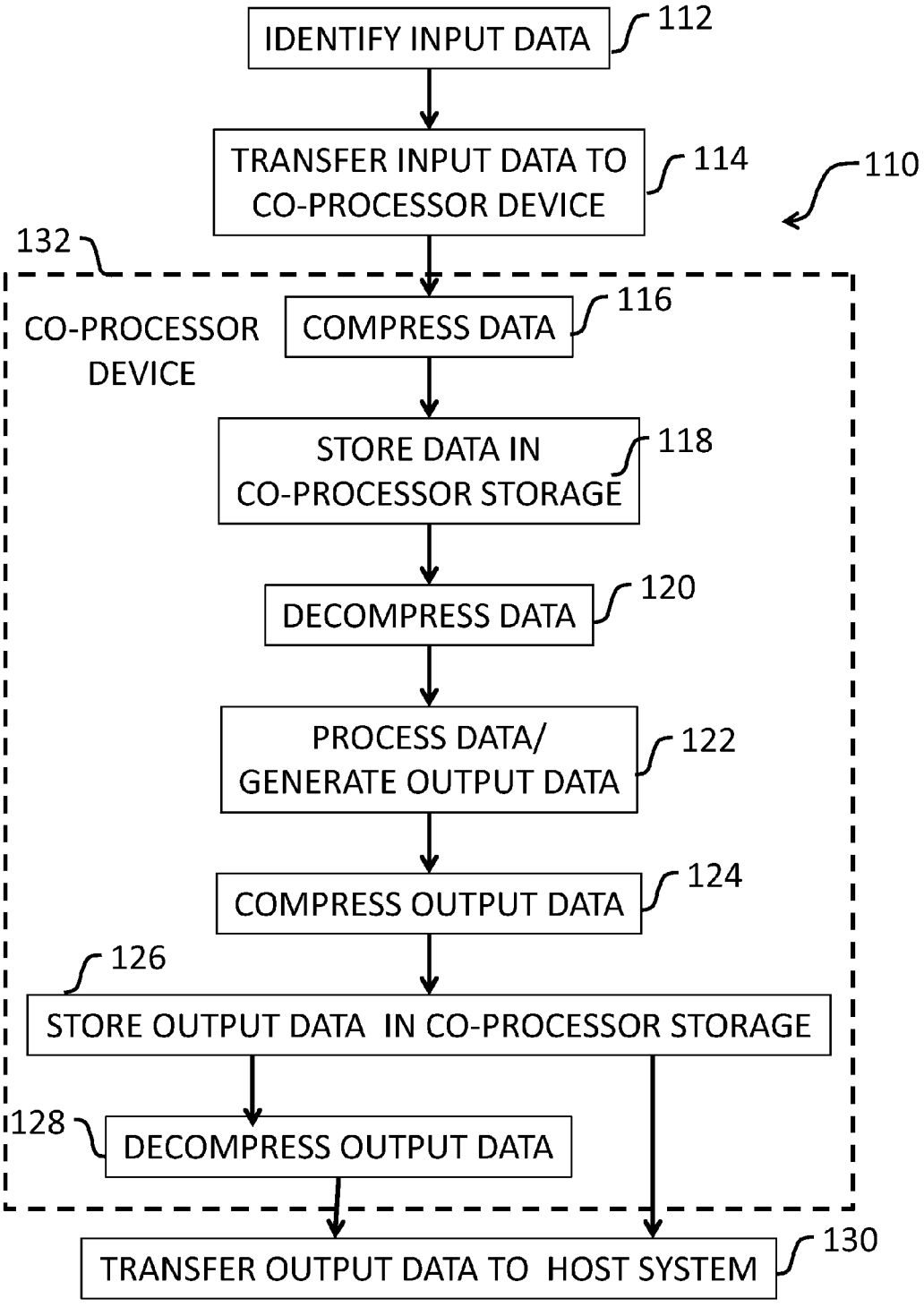

IDENTIFY INPUT DATA
112
TRANSFER INPUT DATA TO CO-PROCESSOR DEVICE
114
110
132
CO-PROCESSOR DEVICE
COMPRESS DATA
116
STORE DATA IN CO-PROCESSOR STORAGE
118
DECOMPRESS DATA
120
PROCESS DATA/ GENERATE OUTPUT DATA
122
COMPRESS OUTPUT DATA
124
126
STORE OUTPUT DATA IN CO-PROCESSOR STORAGE
128
DECOMPRESS OUTPUT DATA
TRANSFER OUTPUT DATA TO HOST SYSTEM
130

FIG. 6

SYSTEM AND METHOD OF PROCESSING SEISMIC DATA ON A CO-PROCESSOR DEVICE

This application is a divisional application of pending U.S. patent application Ser. No. 13/597,466, filed on Aug. 29, 2012, which is a continuation-in-part of U.S. Pat. No. 8,281,056 filed on Jul. 31, 2008, the contents of which are incorporated by reference in their entirety.

FIELD OF THE INVENTION

The invention relates to processing seismic data on at least one co-processor device that is operatively coupled to a host computing system.

BACKGROUND OF THE INVENTION

Generally, computing systems that make use of co-processor devices to perform computation in parallel with central processing units are known. For example, a host computing system may implement a co-processor device to perform computations while the host computing system performs other information processing and/or management functions in order to reduce the processing load on the host computing system. In some instances, co-processor devices may be configured to perform specific types of processing. For example, graphics and/or sound cards (i.e., peripheral devices) may be provided within a host computing system to perform audio and/or video processing, thereby freeing the central processor(s) of the host computing system from having to perform these tasks.

Within the field of seismic earth modeling, host computing systems and co-processor devices have been configured such that certain types of calculations made in determining information related to a seismic volume of interest are performed on the co-processor devices. Such co-processor devices may be specifically tailored to perform the requisite calculations, which may enhance the efficiency of the calculations (e.g., with time-savings, etc.). However, in such conventional configurations, bottlenecks in the processing of information on the co-processor devices may be formed by the need for communication of information between the host computing systems and the co-processor devices, and/or within the co-processor devices themselves.

SUMMARY OF THE INVENTION

One aspect of the invention relates to a method of processing data on a co-processor device that is operatively coupled to a host computing system via a communications channel. In one embodiment, the method comprises receiving a compressed set of input data from the host computing system at the co-processor device over the communications channel, wherein the input data comprises at least one of: a model of a seismic volume of interest and a set of time-varying readings of at least one seismic shot taken by an array of seismic sensors, storing the compressed set of input data to a co-processor information storage, transmitting the stored set of input data to a co-processor, implementing the co-processor to process the input data to determine a set of output data, and transmitting the set of output data to the co-processor information storage or the host computing system.

Another aspect of the invention relates to a method of processing data on a co-processor device that is operatively coupled to a host computing system via a communications channel. In one embodiment, the method comprises receiving input data from the host computing system at the co-processor device over the communications channel, wherein the input data is received by the co-processor device over the communications channel in a compressed format; storing the input data, in its compressed format, to a co-processor information storage included in the co-processor device; transmitting the input data, in its compressed format, from the co-processor information storage to a co-processor included in the co-processor device; implementing the co-processor to decompress the input data; and implementing the co-processor to process the decompressed input data according to a predetermined computational algorithm to produce output data.

Another aspect of the invention relates to a system configured to process data according to a predetermined computational algorithm. In one embodiment, the system comprises one or more system processors, system information storage, a communications channel, and a co-processor device. The one or more system processors manage processes across the system. The system information storage is in communication with the one or more system processors, and the electronic storage of information with the system information storage is managed by the one or more system processors. The communications channel is configured to provide a communication interface between a co-processor device and one or both of the one or more system processors and/or the system information storage. The co-processor device is in communication with one or both of the one or more system processors and/or the system information storage via the communications channel, and includes a co-processor information storage and a co-processor. The co-processor information storage receives information from the one or more system processors and/or the system information storage via the communications channel, the received information comprising input data that has been compressed into a compressed format, and the co-processor information storage stores the input data in the compressed format. The co-processor receives compressed input data from the co-processor information storage, the co-processor being configured to decompress the compressed input data, process the input data according to a predetermined computational algorithm to produce output data, and compress the output data.

Another aspect of the invention relates to a method for processing data on a co-processor device that is operatively coupled to a host computing system via a communications channel wherein a set of input data received by the co-processor device from the host computing system is not compressed. The co-processor device compresses the input data and stores the compressed data on the co-processor information storage. The compressed input data is transmitted to the co-processor on the co-processor device and is processed to determine a set of output data related to the presence of seismic waves in the seismic volume of interest. The set of output data may then be transmitted to the host computing system.

Another aspect of the invention relates to a method for processing data on a plurality of co-processor devices, wherein at least one of the co-processor devices is operatively coupled to a host computing system via a communications channel. The co-processor devices receive input data that may be compressed or uncompressed. If uncompressed, the input data is compressed by the co-processor device. The compressed input data is stored on the co-processor information storage of each co-processor device. The compressed input data is transferred to the co-processors which are

implemented to process the input data to determine intermediate datasets. The intermediate datasets are compressed and transmitted between the co-processor devices over an interconnect device. The intermediate datasets and input datasets are processed by the co-processors. The steps are repeated until a complete set of output data is determined.

Yet another aspect of the invention relates to a system for processing data on a plurality of co-processor devices. In one embodiment, the system includes one or more system processors that manage processes across the system, system information storage in communication with the one or more system processors, a communications channel configured to provide a communication interface between at least one co-processor device and at least one of the system processors and/or the system information storage, and a plurality of co-processor devices each of which include a co-processor information storage, a co-processor, and an interconnect device configured to transmit data to other co-processor devices.

These and other objects, features, and characteristics of the present invention, as well as the methods of operation and functions of the related elements of structure and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the invention. As used in the specification and in the claims, the singular form of "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a system configured to generate readings of at least one seismic shot within a volume of seismic interest, in accordance with one or more embodiments of the invention.

FIG. **2** illustrates a system configured to process data on a co-processor device (e.g. peripheral device) that is operatively coupled to a host computing system, according to one or more embodiments of the invention.

FIG. **3** illustrates a method of processing data on a co-processor device (e.g. peripheral device) that is operatively coupled to a host computing system, in accordance with one or more embodiments of the invention.

FIG. **4** illustrates a system configured to process data on a co-processor device that is operatively coupled to a host computing system, according to one or more embodiments of the invention.

FIG. **5** illustrates a system configured to use a plurality of co-processor devices, according to one or more embodiments of the invention.

FIG. **6** illustrates a method of processing data on a co-processor device that is operatively coupled to a host computing system, in accordance with one or more embodiments of the invention.

DETAILED DESCRIPTION

FIG. **1** illustrates a system **10** configured to generate readings of at least one seismic shot within a seismic volume of interest **12**. System **10** records information related to the rate of propagation and/or the reflection of seismic waves within seismic volume of interest **12**. From the information recorded by system **10**, information related to seismic volume of interest **12** is determined. For example, a velocity model, a density model, an elasticity model, and/or other information related to seismic volume of interest **12** may be specified. In one embodiment, system **10** includes a source **14** and a set of seismic sensors **16**.

In one embodiment, source **14** generates waves within the seismic volume of interest **12**. As such, source **14** is a source of seismic wavefields that propagate through seismic volume of interest **12**. Source **14** may generate seismic waves that enter the seismic volume of interest **12**, and/or source **14** may physically impact the surface of seismic volume of interest **12** to generate the waves. For example, in one embodiment, source **14** includes explosives (e.g., dynamite/Tovex), a specialized air gun, a Vibroseis, and/or other sources.

Seismic sensors **16** are configured to detect seismic wavefields. For example, seismic sensors **16** may include seismometers that generate time varying signals that indicate motion at the surface (or at some point within) seismic volume of interest **12**. In the embodiment illustrated in FIG. **1**, seismic sensors **16** are disposed on a surface of seismic volume of interest **12**. However, this is not intended to be limiting, and in some embodiments, seismic sensors **16** may include instruments that detect subsurface seismic wavefields. Still further, in one embodiment, seismic sensors **16** include instruments disposed on a surface of a body of water located on top of seismic volume of interest **12**, and detect wavefields that propagate up to seismic sensors **16** from an interface between a surface of seismic volume of interest **12** and the water. Seismic sensors **16** are typically disposed in a uniform and/or predetermined manner with respect to seismic volume of interest **12**. For example, seismic sensors **16** may be disposed along a grid at the surface of seismic volume of interest. In another example, seismic sensors **16** may be disposed in the subsurface near and/or within the seismic volume of interest.

As can be seen in FIG. **1**, in one embodiment, system **10** further comprises a storage module **18**. Storage module **18** stores information related to the generation of seismic waves by source **14** and/or the detection of waves by seismic sensors **16**. This information may include positional (and/or orientation) information related to one or both of source **14** and/or seismic sensors **16**, information related to the waves generated by source **14** (e.g., frequency, phase, amplitude, etc.), information related to the time varying signals generated by individual ones of seismic sensors **16**, (e.g., frequency, phase, amplitude, etc.), and/or other information.

In the embodiment illustrated in FIG. **1**, storage module **18** includes a single centralized storage facility that is operatively linked with seismic sensors **16** and/or source **14**. In this embodiment, the operative link between storage module **18**, seismic sensors **16**, and/or source **14** may be accomplished via electronic communication (e.g., wired communication, wireless communication, communication via a network, etc.). In some instances, the operative link between storage module **18** and seismic sensors **16** includes a set of removable electronic storage media that are disposed individually at each of seismic sensors **16** (or are each linked to a set of seismic sensors **16**), and then are removed and transported to the centralized storage facility for storage and/or data transfer. It should be appreciated that the illustration of storage module **18** is not intended to be limiting. In one embodiment, storage module **18** may include a set of distributed storage facilities (e.g., disposed at individual seismic sensors **16**).

FIG. **2** illustrates a system **20** configured to determine information related to a seismic volume of interest. In one embodiment, the information determined by system **20** includes seismic wavefields within the seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source (e.g., source **14** shown in FIG. **1** and described above). As can be seen in FIG. **2**, in one embodiment, system **20** includes host system **22** and a co-processor device such as peripheral device **24**. In particular, system **20** enables the determination of the one or more seismic wavefields to be determined by peripheral device **24** in an enhanced manner (e.g., faster, with a smaller impact on the computing resources of host system **22**, etc.).

Host system **22** represents a host computing system capable of electronically processing information according to predetermined algorithms. In some instances, host system **22** further manages the processing of information by resources outside of host system **22**. For example, host system **22** may manage aspects of information processing performed on peripheral device **24** (e.g., by controlling information provided to peripheral device **24** and/or accepting output data from peripheral device **24**), aspects of information processing performed by other host systems (e.g., in a client-server configuration, in a peer-to-peer configuration, etc.), and/or other processing of information outside host system **22**. In one embodiment, host system **22** includes a system information storage **26**, a processor **28**, and a communications channel such as peripheral bus **30**.

System information storage **26** includes one or more electronically readable storage media that enable information to be electronically stored by system information storage **26**. The electronically readable storage media of system information storage **26** may include one or both of system storage that is provided integrally (i.e., substantially non-removable) with host system **22** and/or removable storage that is removably connectable to host system **20** via, for example, a port (e.g., a USB port, a firewire port, etc.) or a drive (e.g., a disk drive, etc.). System information storage **26** may include one or more of optically readable storage media (e.g., optical disks, etc.), magnetically readable storage media (e.g., magnetic tape, magnetic hard drive, floppy drive, etc.), electrical charge-based storage media (e.g., EEPROM, RAM, etc.), solid-state storage media (e.g., flash drive, etc.), and/or other electronically readable storage media. System information storage **26** may store software algorithms, information related to an output generated by an electronic display associated with host system **20** (not shown), information determined by processor **28**, information transmitted to and/or received from peripheral device **24**, and/or other information that enables host system **22** to process information and/or manage the processing of information properly. System information storage **26** may be a separate component within host system **22**, or system information storage **26** may be provided integrally in the same device(s) as processor **28** (e.g., in a desktop or laptop computer).

Processor **28** is configured to provide information processing capabilities in host system **22**. As such, processor **28** may include one or more of a digital processor, an analog processor, a digital circuit designed to process information, an analog circuit designed to process information, a state machine, and/or other mechanisms for electronically processing information. Although processor **28** is shown in FIG. **2** as a single entity, this is for illustrative purposes only. In some implementations, processor **28** may include a plurality of processing units. These processing units may be physically located within the same device, or processor **28** may represent processing functionality of a plurality of devices operating in coordination to provide the functionality of host system **22**.

As is shown in FIG. **2**, in one embodiment, processor **28** includes an input data module **32**, and a compression module **34**. Modules **32** and **34** may be implemented in software; hardware; firmware; some combination of software, hardware, and/or firmware; and/or otherwise implemented. It should be appreciated that although modules **32** and **34** are illustrated in FIG. **2** as being co-located within a single processing unit, in implementations in which processor **28** includes multiple processing units, modules **32** and/or **34** may be located remotely from the other modules.

As was mentioned above, system **20** may, in some instances, be configured to determine information related to a seismic volume of interest. In order to determine such information, processor **28** may manage processing of information by peripheral device **24**. Information may be processed on peripheral device **24**, for example, to free the computing resources (e.g., system information storage **26** and/or processor **28**) for other processing activities, with an enhanced efficiency (e.g., where peripheral device **24** is configured to perform a certain type of processing more efficiently than processor **28**), and/or for other reasons. The determination of information related to the seismic volume of interest by peripheral device **24** may include a determination of a complete set of output data. For example, a complete set of output data may include one or more seismic wavefields within the seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source (e.g., source **14** shown in FIG. **1** and described above). Other complete sets of output data are also contemplated.

In order to enable peripheral device **24** to perform processing involved in a determination of a complete set of output data related to a seismic volume of interest, input data module **32** may identify a set of input data that will be needed by peripheral device **24** to determine the set of output data. For example, where the set of output data will include one or more seismic wavefields within the seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source, the set of input data needed to determine this set of output data will include one or more complete models of the seismic volume of interest (e.g., a velocity model, a density model, an elasticity model, etc.), readings taken by an array of seismic sensors that each generated time-varying data while waves caused by at least one seismic shot were propagating through the seismic volume of interest, and/or information (e.g., waveform(s), etc.) describing the at least one seismic shot introduced into the seismic volume of interest. The data identified by input data module **32** may include data previously stored on system information storage **26**.

Compression module **34** is configured to compress input data prior to transmission to peripheral device **24**. The compression of input data by compression module **34** may take place immediately prior to the transmission of the compressed input data to peripheral device **24**, or the input data may be compressed by compression module **34** and stored to system information storage **26**, prior to being transmitted from system information storage **26** to peripheral device **24**, in its compressed form. The compression of

the input data tends to enhance various aspects of the operation of system **20**. For example, the transmission of compressed input data from host system **22** to peripheral device **24** effectively increases the rate of transfer of the information being transmitted (e.g., increased by the compression factor). This may remove a system bottleneck caused by a limited rate of information transfer between processor **28** and peripheral device **24**, particularly for transmissions of relatively large amounts of input data. As another example, the transmission of the input data in a compressed form tends to increase the amount of data that can be stored to peripheral device **24**. Other enhancements may be realized through the transmission of compressed input data from host system **22** to peripheral device **24**.

As was mentioned above, from the input data received from host system **22**, peripheral device **24** generates a set of output data. In one embodiment, the set of output data includes one or more seismic wavefields within a seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source. The set of output data is transmitted from peripheral device **24** to host system **22**. In one embodiment, the set of output data received by host system **22** from peripheral device **24** is compressed (e.g., according to the compression implemented on the input data prior to transmission). In this embodiment, compression module **34** decompresses the output data. For example, compression module **34** may decompress the output data as it is received from peripheral device **24**, and/or the output data may first be stored (e.g., to system information storage **26**), and then decompressed by compression module **34** some time after receipt from peripheral device **24**.

In one embodiment, the compression algorithms implemented by compression module **34** to compress and/or decompress input data and/or output data compress data by a compression factor of between about 2 and about 200. In one embodiment, the compression algorithms implemented by compression module **34** to compress and/or decompress input data and/or output data compress data by a compression factor of between about 10 and about 100. For example, the compression algorithms may include representing input data and/or output data with word formats for fixed or floating point numbers that are shorter than 32 bits per sample. As another example, the compression algorithms may include transform-based compression, such as the wavelet transforms described in U.S. Pat. No. 5,745,392 entitled "Method for Reducing Data Storage and Transmission Requirements for Seismic Data," issued Apr. 28, 1998, the contents of which are incorporated by reference into this disclosure in their entirety. The compression factor may be selected such that computations performed on peripheral device **24** become "computation bound" (e.g., bound by the computation speed provided by processor(s) present in host system **22** and/or peripheral device **24**) instead of "I/O bound" (e.g., bound by the time required for the input and/or output of data sets that must be communicated between and/or stored in the various components of system **20**, which is alleviated through compression).

Peripheral bus **30** is configured to enable the transmission of information back and forth between host system **22** and peripheral device **24**. In one embodiment, peripheral bus **30** comprises a Peripheral Component Interconnect ("PCI") bus, or a similar peripheral bus (e.g., PCIe, PCI-X, PCIe-2.0, PCIe-3.0, HTX, etc.) that provides a connection between host system **22** and peripheral device **24**. In this embodiment, peripheral bus **30** may include a socket provided on and/or connected to a motherboard associated with host system **22**, and/or peripheral bus **30** may be formed as a permanent connection between host system **22** and a peripheral device that is integrally formed with host system **22** (e.g., as an integrated circuit fitted onto a motherboard of host system **22**). In one embodiment, peripheral bus **30** comprises some other port and/or communications channel that implements another method for connecting a peripheral device with host system **22** such as Infiniband, Ethernet, Fibre Channel, Interlaken, or any specialized point-to-point protocol. These examples are not meant to be limiting; other communications channels fall within the scope of this invention. Additionally, data may pass over multiple types of communication channels between the main processor and the peripheral device. For example, it could pass from the main processor memory to a network adapter via a peripheral bus (e.g. PCI Express), from the network adapter to the remote endpoint via a network bus (e.g. Infiniband) and then from the remote endpoint network adapter to the peripheral device via a peripheral bus (e.g. PCI Express). Other combinations of communication channels and additional devices between the host system and the peripheral device are possible and fall within the scope of this invention.

As has been stated briefly above, peripheral device **24** is configured to receive input data from host system **22**, process the input data in accordance with one or more predetermined algorithms to generate a complete set of output data, and transmit the output data back to host system **22**. As used herein, the term "co-processor device" or "peripheral device" may include any device that is connected directly to host system **22** to expand the functionality and/or capabilities of host system **22**. For example, in one embodiment, peripheral device **24** includes an expansion card that is connected with host system **22** via peripheral bus **30**. The co-processor device may be located within the same chassis as the host system or remotely from the host system. In one embodiment, peripheral device **24** comprises a peripheral information storage **36** and a peripheral processor **38** and, equivalently, a co-processor device comprises a co-processor information storage and a co-processor.

The co-processor device may have co-processor information storage, such as peripheral information storage **36** which includes an electronically readable storage medium that enables the storage of information (e.g., input data, output data, etc.) on peripheral device **24**. Where peripheral device **24** is formed as a peripheral card, this storage medium typically includes electrical charge-based storage media (e.g., EEPROM, RAM, etc.), and/or solid-state storage media (e.g., flash drive, etc.), however, other electronically readable storage media are contemplated. While system **20** may be formed such that input data and/or output data may be stored to peripheral information storage **36** in a compressed form, peripheral information storage **36** may not typically include processing resources for compressing/decompressing information. Instead, peripheral information storage may generally be configured to merely store information in the form in which it is received (e.g., a compressed form).

In conventional peripheral devices, particularly peripheral card devices, the included peripheral information storage tends to be relatively small. For example, less than about 1 Gigabyte. As another example, less than about 4 Gigabytes. As still another example, less than about 6 Gigabytes. By contrast, peripheral information storage **36** is relatively large. For example, peripheral information storage **36** may be greater than or equal to about 24 Gigabytes. As another example, peripheral information storage **36** may be greater

than or equal to about 48 Gigabytes. As yet another example, peripheral information storage **36** may be greater than or equal to about 96 Gigabytes. These numbers represent the current state of conventional peripheral devices and peripheral information storage **36**; these numbers are for comparison of relative sizes only and are not meant to be limiting. The enhanced size of peripheral information storage **36** may enable a relatively large amount of information to be held on peripheral device **24**. As will be discussed further below, in one embodiment, the size of peripheral information storage **36** may be such that peripheral device **24** holds enough compressed input data to enable peripheral device **24** to perform an entire processing operation without limiting the speed of the processing operation in waiting for additional information (e.g., additional input data) from host system **22**.

Since the communication of information from host system **22** to peripheral device **24** over peripheral bus **30** may act as a bottleneck in the processing of information on peripheral device **24** (e.g., peripheral device **24** is capable of processing information at a substantially greater rate than information can be communicated between peripheral device **24** and host system **22** over peripheral bus **30**), holding enough of the compressed input data required to perform an entire processing operation on peripheral information storage **36** such that the communication of amounts of additional compressed input data not initially stored on peripheral information storage **36** does not limit the speed at which the processing operation is performed. This may enhance the speed at which the processing operation can be performed by peripheral device **24**. In some implementations, the compressed data stored in peripheral information storage **36** may include all of the input data required for the processing operation. In some implementations, the compressed input data stored in peripheral information storage **36** may include substantially all of the input data required for the processing operation such that reduction in speed of the processing operation caused by the communication of additional input data required for the processing operation will be de minimis.

As used herein, the term "entire processing operation" may refer to a processing pass through an entire input data set, including all of the inner loops within the processing. For example, in one embodiment, an entire processing operation may include determining one or more seismic wavefields within a seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source. In order to facilitate this processing without requiring substantial requests for data from host system **22** during the operation, peripheral information storage **36** may be configured to hold all (or substantially all) of one or more of at least one complete model of a seismic volume of interest, a complete set of readings of at least one seismic shot within the seismic volume of interest (e.g., a single shot, one or more common offset cubes, one or more common midpoint gather, one or more common receiver gather, etc.) taken by an array of seismic sensors that each generated time-varying data during the at least one seismic shot, and/or wavelets that represent seismic waves introduced into the seismic volume of interest during the at least one seismic shot by a seismic source.

Where peripheral information storage **36** holds substantially all, but not entirely all, of the entire set of input data, input data module **32** of processor **28** may be configured to determine how much of the entire set of input data may be excluded from storage within peripheral information storage **36** initially (and communicated via peripheral bus **30** during computation) without interfering significantly with the speed of the computation. This determination may be dynamic (e.g., based on conditions within system **20** and/or the specific computation to be performed) and/or static (e.g., a predetermined percentage of the overall set of input data). Where the determination is dynamic, input data module **32** may determine the portion of the entire set of input data to be excluded from storage within peripheral information storage initially based on one or more of a data transfer rate over peripheral bus **30**, a compression factor of the input data, a size of the entire input data set, a computational speed of peripheral device **24**, a complexity of the computation to be performed on the set of input data, and/or other factors.

Peripheral processor **38** is configured to provide information processing capabilities in peripheral device **24**. As such, peripheral processor may include one or more of a digital processor, an analog processor, a digital circuit designed to process information, an analog circuit designed to process information, a state machine, and/or other mechanisms for electronically processing information. Although processor **28** is shown in FIG. **2** as a single entity, this is for illustrative purposes only. In some implementations, processor **28** may include a plurality of processing units.

In one embodiment, peripheral processor **38** includes a Field-Programmable Gate Array ("FPGA"). An FPGA is a semiconductor device containing programmable logic components called "logic cells" (e.g., flip-flops) and/or "logic blocks" (e.g., multiplication or memory blocks), and programmable interconnects there between. Logic cells and/or blocks can be programmed to perform the function of basic logic gates such as AND, and XOR, or more complex combinational functions such as decoders or mathematical functions. A network of programmable interconnects allow logic cells and/or blocks to be interconnected as needed by the system designer, somewhat like a one-chip programmable breadboard. Logic cells and/or blocks and interconnects can be programmed by the customer or designer, after the FPGA is manufactured, to implement any logical function—hence the name "field-programmable".

FPGA's may enhance processing (e.g., speed, power consumption, etc.) in repetitively processing large data sets with respect to the processing capabilities of other less specialized processors (e.g., processor **28**). In fact, this enhanced efficiency provides an impetus for processing input data on peripheral device **24** in some instances. For example, where peripheral device **24** is implemented to generate one or more seismic wavefields within a seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source, an FPGA may provide an enhanced speed for the requisite processing, in addition to alleviating the processing load on processor **28**.

In one embodiment, peripheral processor **38** may include one or more of a compression module **40**, a processing module **42**, and/or other modules. Modules **40** and **42** may be implemented in software; hardware; firmware; some combination of software, hardware, and/or firmware; and/or otherwise implemented.

As has been mentioned above, in one embodiment, input data is transmitted to peripheral device **24** and stored on peripheral information storage **36** in a compressed form. Compression module **40** is configured to decompress input data stored on peripheral information storage **36**. In addition to enabling the storage of compressed input data on peripheral information storage **36** (thereby increasing the amount

of input data that can be stored on peripheral information storage **36**), the ability of compression module **40** to decompress input data on peripheral processor **38** further increases the rate at which information is transferred in peripheral device **24** (by the compression factor). Since the transmission of information between peripheral information storage **36** and peripheral processor **38** can present a bottleneck in the processing of information on peripheral device **24**, the enhancement in the rate of information transfer realized by transmitting compressed input data to peripheral processor **38** from peripheral information storage **36** may provide a significant increases in processing efficiency (e.g., time savings, etc.) on peripheral device **24**. In some implementations, the communication of compressed information between peripheral information storage **36** and peripheral processor **38** may transform processes that are I/O bound (e.g., bound by the amount of time required to communicate the requisite information through the bottleneck between these components) to processes that are computation bound (e.g., bound by the computational power provided by peripheral processor **38**).

Processing module **42** may process the input data that is decompressed by compression module **40** to generate output data. For example, where the output data generated includes one or more seismic wavefields within a seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source, processing module **42** may include imaging or seismic processing algorithms.

Once output data has been generated by processing module **42**, compression module **40** then compresses the output data. The output data may be compressed according to compression algorithms that are the same, or similar, to the compression algorithms used to compress the input data. Compression of the output data may provide one or more of several enhancements to system **20**. For example, compression of the output data on peripheral processor **38** may enhance the rate at which the output data is transferred from peripheral processor **38** to peripheral information storage **36**, the rate at which output data is transferred from peripheral device **24** to host system **22** over peripheral bus **30**, and/or the amount of output data that can be stored in peripheral information storage **36**.

In the embodiment in which peripheral processor **38** comprises an FPGA, input data is received by peripheral processor **38**, and flows through the logic blocks of peripheral processor **38** according to the interconnects established for a predetermined computation. More specifically, compressed input data is first provided to the logic blocks associated with compression module **40** for decompression, then is routed through the logic blocks associated with processing module **42** to generate output data, and then the output data is routed through the logic blocks associated with compression module **40** to compress the output data for transmission to peripheral information storage **36**. From peripheral information storage **36**, the compressed output data is transferred to host system **22**.

FIG. **3** illustrates a method **44** of processing data on a peripheral device that is operatively coupled to a host computing system via a peripheral bus. Although the operations of method **44** are discussed below with respect to the components of system **20** described above and illustrated in FIG. **2**, it should be appreciated that this is for illustrative purposes only, and that method **44** may be implemented with alternative components and/or systems without departing from the scope of this disclosure. Further, the operations of method **44** presented below are intended to be illustrative. In some embodiments, method **44** may be accomplished with one or more additional operations not described, and/or without one or more of the operations discussed. Additionally, the order in which the operations of method **44** are illustrated in FIG. **3** and described below is not intended to be limiting.

At an operation **46**, input data to be processed is identified. The input data includes a complete set of input data that will enable an entire processing operation to be performed. In some instances, the entire processing operation may include determining information related to a seismic volume of interest. For example, the information related to the seismic volume of interest may include one or more seismic wavefields within the seismic volume of interest at a given point in time during which seismic waves are present in the seismic volume of interest as a result of one or more seismic shots produced by a seismic source. In such instances, the complete set of input data may include one or more of one or more complete models of the seismic volume of interest (e.g., a velocity model, a density model, an elasticity model, etc.), readings taken by an array of seismic sensors that each generated time-varying data while waves caused by at least one seismic shot were propagating through the seismic volume of interest, and/or information (e.g., waveform(s), etc.) describing the at least one seismic shot introduced into the seismic volume of interest. In one embodiment, operation **46** is performed by an input data module of the host computing system that is the same as, or similar to, input data module **32** (shown in FIG. **2** and described above).

At an operation **48**, input data identified at operation **46** is compressed. In one embodiment, operation **48** is performed by a compression module of the host computing system that is the same as, or similar to, compression module **34** (shown in FIG. **2** and described above).

At an operation **50**, the compressed input data is transferred from the host computing system to the peripheral device over the peripheral bus. As such, operation **50** includes the transmission of the compressed input data by the host computing system and the reception of the compressed input data by the peripheral device.

At an operation **52**, the compressed input data is stored on the peripheral device. The set of input data stored simultaneously on the peripheral device at operation **52**, in one embodiment, comprises an entire set of input data that enables an entire processing operation to be performed on the input data with a reduced, or eliminated, requirement for reception of additional input data at the peripheral device to complete the entire processing operation. For example, in some instances, the entire set of input data includes one or more of one or more complete models of the seismic volume of interest (e.g., a velocity model, a density model, an elasticity model, etc.), readings taken by an array of seismic sensors that each generated time-varying data while waves caused by at least one seismic shot were propagating through the seismic volume of interest, and/or information (e.g., coefficient(s), etc.) describing the at least one seismic shot introduced into the seismic volume of interest. In one embodiment, operation **52** comprises the storage of the entire set of input data to a peripheral information storage formed on the peripheral device that is the same as, or similar to, peripheral information storage **36** (shown in FIG. **2** and described above).

At an operation **54**, the compressed input data is transferred within the peripheral device from the peripheral storage to a peripheral processor formed on the peripheral device. As such, operation **54** includes the transmission of

compressed input data from the peripheral information storage, and the receipt of compressed input data by the peripheral processor. In one embodiment, the peripheral processor is the same as, or similar to, peripheral processor **38** (shown in FIG. **2** and described above).

At an operation **56**, the peripheral processor decompresses the received input data. In one embodiment, operation **56** is performed by a compression module that is the same as, or similar to, compression module **40** (shown in FIG. **2** and described above).

At an operation **58**, decompressed input data is processed in accordance with one or more predetermined algorithms to generate output data. In one embodiment, operation **58** is performed by a processing module that is the same as, or similar to, processing module **42** (shown in FIG. **2** and described above). It should be appreciated that in some instances, operation **58** may be implemented as a hybrid of operations **56** and **58** above, wherein compressed (or partially compressed) input data may be processed without decompression (or complete decompression).

At an operation **60**, the peripheral processor compresses the output data generated at operation **58**. In one embodiment, operation **60** is performed by the compression module that performed operation **56**.

At an operation **62**, the compressed output data is transferred from the peripheral processor to the peripheral information storage. As such, operation **62** includes the transmission of the compressed output data from the peripheral processor, and the reception of the compressed output data by the peripheral information storage.

At an operation **64**, the compressed output data is stored on the peripheral device. In one embodiment, the compressed output data is stored on the peripheral information storage.

At an operation **66**, the compressed output data is transferred from the peripheral device to the host computing system via the peripheral bus. As such, operation **66** comprises the transmission of the compressed output data from the peripheral device, and the receipt of the compressed output data at the host computing system.

At an operation **68**, the compressed output data is decompressed on the host computing system. In one embodiment, operation **68** is performed by the compression module that performed operation **48**.

It should be appreciated that the description of system **20** and method **44** in the context of determining information related to a seismic volume of interest has been provided herein merely for illustrative purposes. This disclosure includes within its scope other embodiments in which the management and transmission of compressed information within and between a host computing system and a peripheral device in the manner described herein enhances the efficiency of processing managed by the host computing system on the peripheral device. Such enhancements in the processing efficiency may be a result of one or more of increasing the effective rate of data transferred between the host computing system and the peripheral device, increasing effective storage space for input data on the peripheral device (thereby reducing and/or eliminating the need for the peripheral device to receive input data in an ongoing manner during data processing), and/or increasing the effective rate of data transferred within the peripheral device between storage and processing.

Another embodiment of the invention is illustrated in FIG. **4** and FIG. **6**. In this embodiment, the bottleneck is not between the host computer system and the co-processor device but rather between the co-processor and the co-processor information storage. In method **110** of FIG. **6**, the input data is identified by the host computer system at operation **112**. The host system **70** in FIG. **4** then transfers the input data through a communications channel **88** to co-processor device **72** at operation **114** without compressing the data first. When the co-processor **74** receives the input data, it executes compression module **80** to compress the data at operation **116** and stores it on the co-processor information storage **76** at operation **118**. When the co-processor device **72** enters a computation phase, it reads the compressed data from its co-processor information storage **76** into its co-processor **74** and decompresses it at operation **120**. The decompression module **82** transforms the compressed data into a format suitable for computation by the computation module **78**, which processes the data to generate output data as at operation **122**. The decompression module may decompress all or part of the data and may decompress it into a format that is the same as the original input data from the host system **70** or into a different format that is suitable for the computation module **78**. After the co-processor **74** has completed all or part of the processing at operation **122**, the output data is compressed by compression module **80** at operation **124** and stored on co-processor information storage device **76** at operation **126**. The compression module **80** for the output data at operation **124** may be different from the compression module **80** for the input data at operation **116**. The co-processor information storage device **76** for the compressed output data at operation **126** may be different from the co-processor information storage device **76** for the compressed input data at operation **118**. The output data may be transferred to the host system **70** at operation **130** as either compressed output data by communications channel **86** or decompressed output data which is decompressed by the decompression module **82** on the co-processor **74** then transferred through the communications channel **84**. The communications channels **84**, **86**, and **88** may all be the same devices or different devices and may be, by way of example and not limitation, one or more of a PCI bus, a PCIe bus, a PCI-X bus, a PCIe-2.0 bus, a PCIe-3.0 bus, an HTX bus, Infiniband, Ethernet, Fibre Channel, Interlaken or any specialized point-to-point protocol. In the method **110** of FIG. **6**, the co-processor device **132** may perform operations **116-128**.

In yet another embodiment, the systems illustrated in FIG. **2** and FIG. **4** may include more than one co-processor device. These devices may be connected directly to the host system, as co-processor device **24** is connected to host system **22** and co-processor device **72** is connected to host system **70** and/or the co-processor devices may be connected to each other. FIG. **5** illustrates a system wherein multiple co-processor devices **90** are linked to each other. The host system **106** may be connected to one or multiple co-processor devices through one or more communications channels, which may link to one or more of the co-processor information storages **94** and/or one or more of the co-processors **92** at the compression modules **100**. In this example, each of the co-processor devices **90** contain a co-processor **92** capable of executing the decompression modules **98**, compression modules **100**, and computation modules **96**. These modules may perform processing operations similar to those performed by the like-named modules previously described in FIG. **4**. In FIG. **5**, the co-processor devices **90** also have interconnect device **102**. These interconnect devices **102** allow the co-processor devices to transfer information over a communications channel **104**, which may be, for example, one or more of a PCI bus, a PCIe bus, a PCI-X bus, a PCIe-2.0 bus, a PCIe-3.0 bus, an HTX

bus, Infiniband, Ethernet, Fibre Channel, Interlaken, or a specialized point-to-point protocol. The interconnect devices may be a switched interconnect (e.g. Ethernet, Infiniband, PCI Express) or a point-to-point interconnect (e.g. parallel data bus or high speed serial bus).

The system of FIG. **5** may be used when the computations performed on the input data need to be done on multiple co-processor devices that require information from each other in order to process the data. For example, in the computation of a timestep of a wave modeling calculation, wavefields are stored in a compressed format in memory, for example on the co-processor information storages **94**. The problem domain is decomposed across several co-processor devices **90**, each of which computes a block. To compute a timestep, each co-processor device **90** requires some data from adjacent devices. To compute, the compressed wavefields are loaded from the memories into the co-processors **92**. The input data is passed through the decompression module **98** and into the computation module **96** to perform the computation. The computation module **96** may generate intermediate data or output data. Intermediate data may be sent through the interconnect device **102** by the communications channel **104** to adjacent co-processors in the compressed form (i.e. prior to passing through the decompression module). On arrival at the other co-processor, the intermediate data is decompressed **98** and passed to that co-processor's computation module **96**. The computation module **96** may use the input data from its own co-processor information storage, its own intermediate data, and intermediate data transmitted to it from other co-processor devices to repeat processing steps until a complete set of output data has been determined Output data from the computation module **96** can be transferred to another co-processor **92** by passing it through a compression module **100** before transmitting it through the interconnect device **102** by the communications channel **104** and/or may be transmitted to the host system **106**.

Although the invention has been described in detail for the purpose of illustration based on what is currently considered to be the most practical and preferred embodiments, it is to be understood that such detail is solely for that purpose and that the invention is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims. For example, it is to be understood that the present invention contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

What is claimed is:

1. A method of processing data on a co-processor device that is operatively coupled to a host computing system via a communications channel, the method comprising:

receiving a set of input data from the host computing system at the co-processor device over the communications channel, wherein the input data is received by the co-processor device over the communications channel in an uncompressed format, and wherein the set of input data comprises one or both of (i) one or more models of a seismic volume of interest, and/or (ii) a set of readings of at least one seismic shot within the seismic volume of interest taken by an array of seismic sensors that each generated time-varying data during the at least one seismic shot; compressing the input data on the co-processor device;

storing all or substantially all of the set of compressed input data to a co-processor information storage contained within the co-processor device;

transmitting at least a part of the input data included in the stored set of input data, in its compressed format, from the co-processor information storage to a co-processor included in the co-processor device;

implementing the co-processor to process the part of the input data received from the co-processor information storage to determine a set of output data related to the presence of seismic waves in the seismic volume of interest; and

transmitting the set of output data related to the presence of seismic waves in the seismic volume of interest to the co-processor information storage or the host computing system over the communications channel.

2. The method of claim **1** wherein implementing the co-processor comprises a decompression module and a computation module.

3. The method of claim **1** wherein transmitting the set of output data transmits a compressed set of output data or an uncompressed set of output data.

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